Chapter 8

SUMMARY AND CONCLUSIONS

8.1 Introduction

This thesis addresses the study of radiation induced effects on semiconductor devices, namely Bipolar Junction Transistors. Few indigenously made BJTs, which are planned for use in space applications by Indian Space Agency have been selected to study the radiation response. The present study gains importance as there is a need to use more and more indigenously made devices for space applications. Further, it is necessary to characterize these devices for radiation response in comparison to devices of the same family from international vendors.

Bipolar junction transistors of the type 2N2219A (*npn*), 2N3019 (*npn*) and 2N2905A (*pnp*) of Continental Device India Ltd (CDIL) make have been chosen for the present study. All these transistors are switching transistors and the forward current gain is an important parameter from the point of application of these devices. These BJTs are exposed to (i) Co^{60} ã- ray (at ISAC, Bangalore), (ii) 8 MeV electron (at Microtron, Mangalore University) and (iii) 24 MeV proton (at NSC, New Delhi) to understand the radiation induced degradation mechanism. In-situ measurements of the changes in the electrical parameters are made as a function of accumulated dose/fluence. The forward current gain of the transistors are measured as a function of accumulated dose/fluence. Gummel plots were also obtained to get better insight into the mechanism of gain degradation. In addition to this, study of heavy ion induced effects on few imported VLSI devices has also been carried out. A theoretical simulation of the variation of displacement damage factor as a function of energy and rad equivalence fluence for various particulate radiation viz., proton, Si, Cl, Ti, Ni, Br, Ag and Au ions is also carried

out. The present study is able to establish few important aspects of radiation induced effects.

8.2 Observations and conclusions

1. Exposure of the devices to ^{60}Co γ-radiation has resulted in considerable current gain degradation. The *npn* transistor is found to degrade as much as the *pnp* transistor, a fact not well established in the literature. Of the two possible mechanisms contributing to gain degradation, viz., *surface degradation* and *bulk degradation*, it appears from the present study that the bulk degradation is the dominant mechanism. Gamma radiation produces bulk degradation through the generation of secondary electrons. These secondary electrons in turn produces atomic displacements. Displacement related defect centers contribute to reduction in minority carrier lifetime. A reduction in minority carrier lifetime results in the degradation of the forward current gain.

2. Exposure of the devices to 8 MeV electrons also results in considerable current gain degradation as a function of accumulated electron dose. Again the displacement damage produced by energetic electrons appears to be the major mechanism contributing to gain degradation.

3. Exposure of the devices to 24 MeV protons has resulted in significant current gain degradation in the *npn* transistor. The estimated displacement damage factors are

consistent with the values reported in the literature for other BJTs of the similar family.

4. Further, it is found that protons are more damaging than the γ-rays and electrons as far as current gain degradation is concerned. A comparison of the degradation of forward current gain (h_{FE}) of one of the transistor 2N 2219A (*npn*) is shown in Figure 8.1. It is clear from the plot that the magnitude of the γ-ray and electron induced current gain degradation is almost same. On the other hand, the magnitude of the gain degradation is larger after proton irradiation.

5. The displacement induced defect and recombination centers, which play a major role in current gain degradation, do not anneal even at 150 ^{o}C. The damage may thus be called permanent damage.

6. All the transistors investigated are switching transistors. One important parameter for a switching transistor is the current gain and it is important to assess the gain degradation of these transistors when they need to be operated in a radiation environment.

7. A theoretical simulation of the energy and fluence dependence of heavy ion induced displacement damage factors for bipolar junction transistors has also brought about certain important results. The estimated displacement damage factors in silicon bipolar junction transistors monotonically increase as the mass number of the ion

increases. The damage factor also increases as the energy of the ion increases upto an energy corresponding to maximum LET and then decreases with increasing energy for a given heavy ion. The maximum value of damage factor decreases as the accumulated rad equivalent fluence increases for a ion of given energy. The estimated variation of damage factor with energy and fluence serves to predict approximately the order of the damage factor and its variation with fluence and energy. The results are almost consistent with the experimentally measured damage factor and its variation as a function of electron and proton fluence. Thus the theoretical simulation has indicated that the mechanism of radiation induced displacement damage appears to be almost similar for light as well as for heavy ions.

8. The indigenous devices degrade similar to devices of the same family from international vendors. Thus as far as the radiation response is concerned, these devices are in par with global quality. There is a need to establish the radiation response of a large number of such devices planned for use in space applications. In order to characterize the devices for radiation induced effects, particle accelerators are required to be used. In India, there are only few particle accelerators and in-situ experiments using particle beams as a function of particle fluence consumes enormous length of beam time. Particle accelerators now-a-days are becoming expensive to use and also the demand for beam time is enormous. Thus it is felt that the study of radiation induced effects using particle accelerators is a laborious and time consuming effort. Thus there is enough scope for semi-empirical approach.

9. Heavy ion testing of few QML class V, class H-grade VLSI devices for Single Event Effect is also carried out on the following types of devices using five types of ions namely Si, Cl, Ti, Ni, and Ag:
   - Field Programmable Gate Array (FPGA) RT 1280 (Rad Tolerant Version) of M/s. Actel, USA.
   - 1553 Bus Controller, BU 61580 (Class H-grade) of M/s. ILC-DDC, USA.
   - 1553 Bus Controller, Summit, 69151 DXE (QML Class V) of M/s. Aeroflex-UTMC, USA.

   Based on the results obtained for heavy ions testing of the investigated devices, the following inference has be drawn:

   (i) FPGA does not appear to be susceptible to SEL even though a few upsets are observed. The device may be used for LEO applications.

   (ii) Summit 69151 DXE MIL-STD-1553 Bus Controller appears to have high SEU LET latchup immunity and thus appears to be suitable for space applications.

   (iii) BU 61580 MIL-STD-1553 Bus Controller appears to be vulnerable to SEE and hence may not be suitable for space applications.

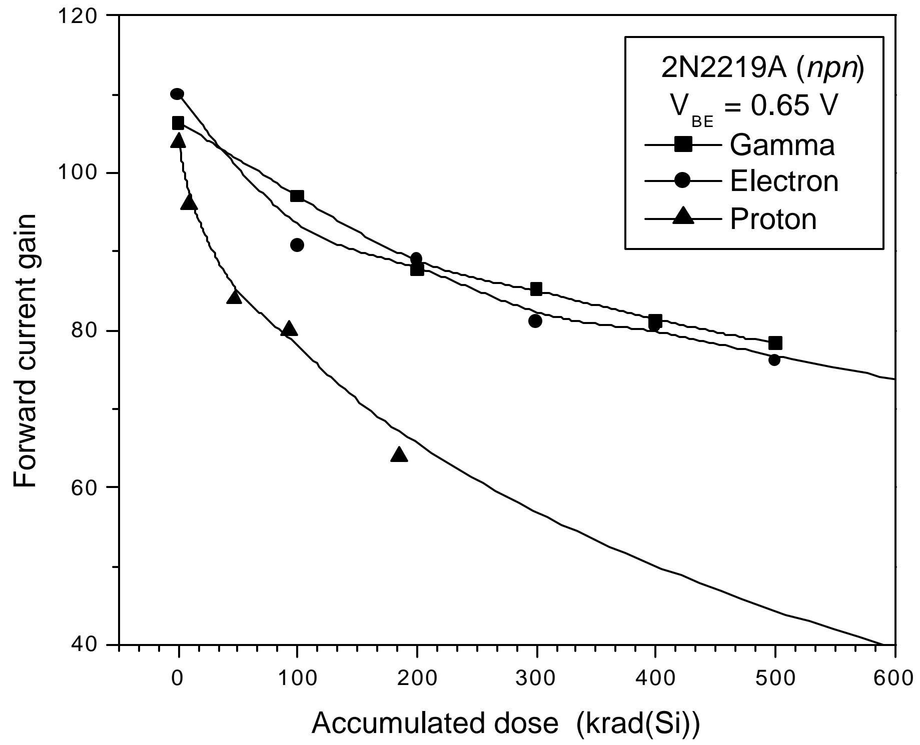

Figure 8.1 Forward current gain as a function of accumulated dose (krad(Si)).

Appendix - I

Proton induced effects on MOS device

Introduction

Metal oxide semiconductor transistors work on the principle of an electrically controlled depletion width. From a bulk damage point of view, it is established that a MOS transistor is superior to ordinary transistors because conductivity changes in the channel are the controlling factor for bulk degradation. However, MOS devices are known to be very sensitive to radiation effects on the surfaces, which occur long before bulk conductivity is affected greatly. Over the years reasonable understanding of radiation effects on MOS device has emerged and moderately fair to excellent models are available for the different effects [1-10].

The MOS device consists of three layers i.e. metal, oxide and semiconductor. The effects of radiation are severe in the oxide (SiO_2) and at interface (Si/SiO_2) [1-2]. The change in the electrical parameters of the device depends on the nature of the impinging particle as well as the MOS structure [3]. In the case of electromagnetic radiation, the ionization effect is predominant, while with charged particle radiation, both ionization and displacement effects have equal importance. High-energy proton often causes detrimental effects on the characteristics of MOS devices and circuits. The threshold voltages, current drives and leakage currents of MOS transistors change due to a change in number of factors.

The following sections describe the results of the effect of proton irradiation on a MOS transistor.

International Rectifier make power MOSFET, 2N6764 which are being employed for space application, have been exposed to 24 MeV proton beam. Irradiation was carried out in the Radiation Biology beam line and the devices were mounted on a glass epoxy PCB. The set up was kept at atmospheric pressure and at room temperature. The decapped devices were exposed to 24 MeV proton with a flux of 5 $x10^5$ particals/cm^2/sec. The total fluence over the exposure period was about $5x10^{10}$ particals/cm^2. Originally, the experiment was planned to study the changes in the electrical characteristics as a function of proton fluence. A completely automated test set-up was made for this purpose. However due to some error in the interfacing and monitoring software, in-situ measurements as a function of accumulated dose could not be performed. Therefore, only off-line measurements were made using TESEC transistor tester unit at ISAC, Bangalore.

Results and discussions

Figure A1 shows the variation of drain current I_D as a function of gate-source voltage V_{GS} before and after proton irradiation for a fluence of 5×10^{10} particles/cm^2. It is seen from the plot that the threshold voltage V_{GS} decreases by about 0.7 V after irradiation. Further, the gate current (I_{GSS}) and drain current (I_{DSS}) of the device measured before and after irradiation are shown in Table A1.

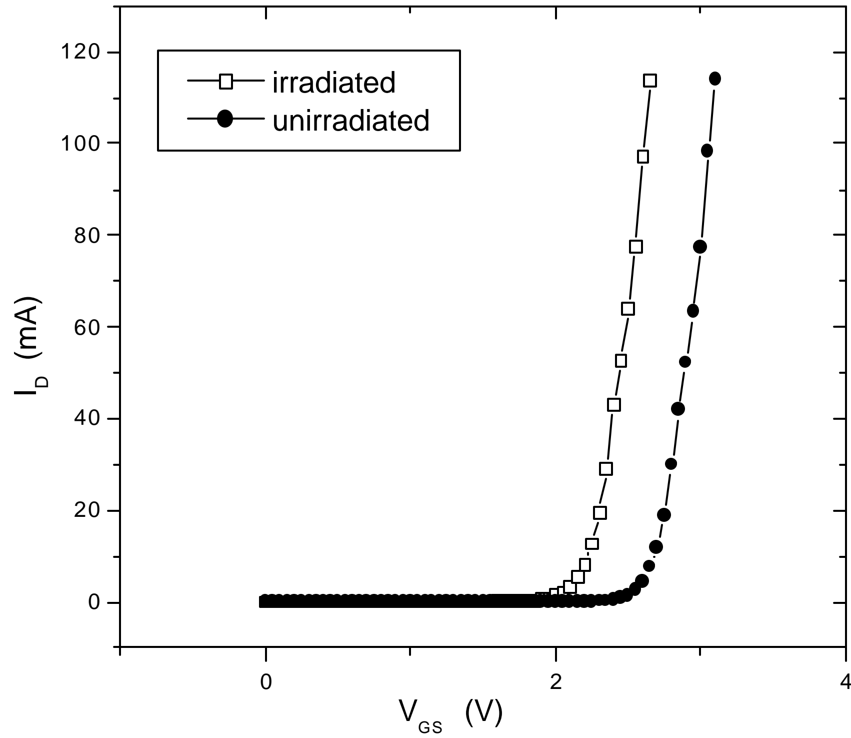

Figure A1 Drain current (I_D) as a function of gate-source voltage (V_{GS}) for pre and post proton irradiation.

Table.A1 TESEC results.

Parameter	Pre-Irradiated	Post-Irradiated
V_{GSTH}	2.627 V	1.990 V
I_{GSS}	17.8 nA	78.40 nA
I_{DSS}	30.0 nA	83.0 nA

The observed changes in the electrical parameters of the MOS device may be explained on the basis of the energy band diagram of the MOS structure.

A schematic energy band diagram for a MOS structure is shown in Figure A2 [1]. The positive bias applied to the gate facilitates the sweeping of free electrons in the oxide layer towards the gate and holes will be attracted to the Si substrate. Also indicated in Figure A2 are the four major basic processes contributing to the radiation response of such a system.

In a MOS device, the oxide-insulating layer (SiO_2) is most sensitive to radiation. When radiation passes through the oxide, the energy deposited creates electron-hole pairs. In SiO_2, the radiation generated electrons are much more mobile than the holes and they are swept out of the oxide (collected at the gate electrode) in times of the order of picosecond [4-5]. However in that first picosecond or two, some fraction of the electrons and holes will recombine. This fraction depends greatly on the applied field and on the energy and type of the incident radiation. The holes which escape initial recombination are relatively immobile and remain behind near their points of generation, causing negative voltage shifts in the electrical characteristics i.e. threshold voltage (V_{TH}) of MOSEFTs. These initial processes of pair creation and recombination, which determine the actual charge (hole) yield in the SiO_2 film and consequently the initial (maximum) voltage shift, constitute the first major factor of the MOS response. Over a period of time extending typically at room temperature from 10^{-7}s to the order of seconds (but much

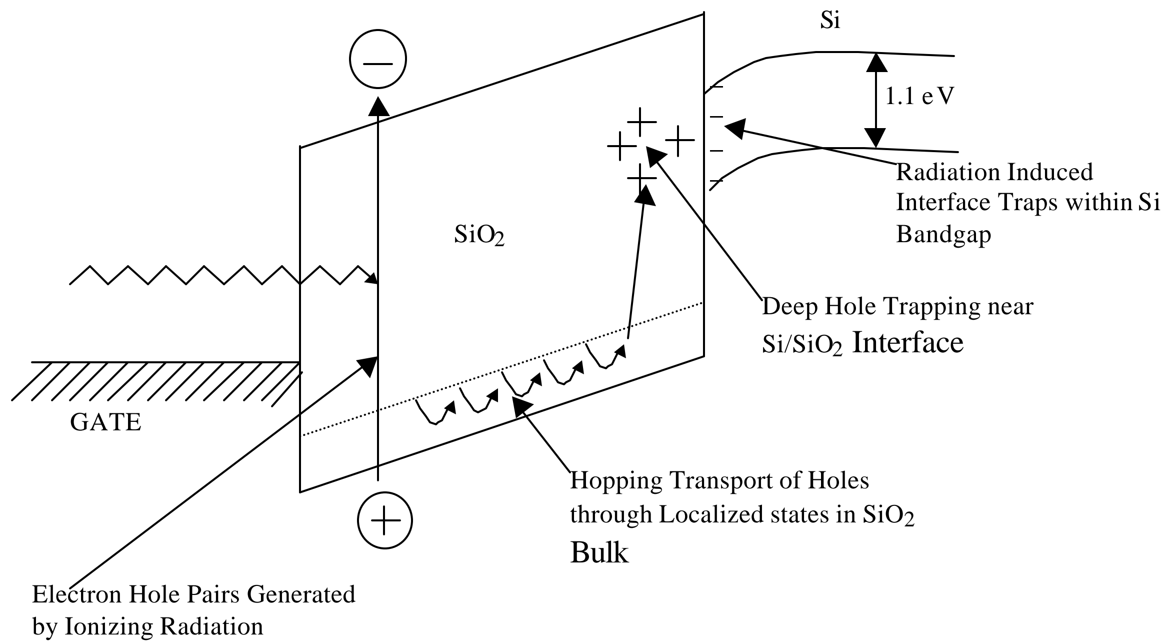

Figure A2 Schematic energy band diagram showing the major radiation effects in a MOS device with positive gate voltage.

longer at lower temperatures) the holes undergo a rather anomalous stochastic hopping transport through the oxide in response to any electric fields present. They move towards the Si substrate for the gate bias situation depicted in Figure A2. This hole transport process, which is very dispersive in time, is the second major factor of the MOS response. It gives rise to a short-term, transient recovery in the voltage shifts and is sensitive to many variables including primarily applied filed, temperature and oxide thickness, and to a lesser extent, oxide process history.

When the holes reach the SiO_2 interface (for applied gate bias), some fractions of them are captured in long term trapping sites, and cause a remnant negative voltage shift that is not sensitive to the silicon substrate potential and which can persist in time for hours to years. This long live radiation induced voltage shift component is the most commonly observed form of radiation damage in MOS devices. The long term trapping of holes near the SiO_2/Si interface, as well as their subsequent annealing in time, constitutes the third major factor of MOS response. Hole trapping and annealing are very sensitive to the processing of the oxide and to other variables such as field and temperature.

The fourth and final component of MOS response is that of a radiation induced build-up of interface traps right at the SiO_2/Si interface. These are localized states with energy levels within Si band gap. Their occupancy is determined by the location of the Fermi levels at the interface and consequently, the radiation induced interface traps give rise to a voltage shift component, which depends on the silicon surface potential. In general, there can be both prompt interface traps present immediately after radiation pulses, as

well as delayed time-dependent build up of states, which can continue for thousands to tens of thousands of seconds at room temperature. Both the magnitude and nature (relative ratio of prompt and delayed components) of the interface traps are also highly dependent upon oxide processing, as well as upon other variables such as temperature and applied field [6].

A major consequence of the radiation-induced charging of the SiO_2 film (including transporting holes, trapped holes and interface traps) is a shift in pertinent voltage operating points for devices, such as in the threshold voltage V_{TH} for a MOSFET. One can write the threshold voltage as

$$V_{TH} = V_{TH0} + \Delta V_{TH}$$

where V_{TH0} is the threshold voltage before irradiation and ΔV_{TH} is the voltage shift due to high-energy particle irradiation. The present power MOSFET 2N6764, when exposed to a proton fluence of 5×10^{10} p/cm^2, the threshold voltage V_{GS} is found to reduce by about 0.7 V. This magnitude of voltage shifted is considerable and thus the MOS devices investigated is found to be sensitive to proton irradiation.

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